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Japan Technology Program Assessment

Precision Engineering/ Precision Optics in Japan

Chris J. Evans

U.S. DEPARTMENT OF COMMERCE
Technology Administration
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U.S. DEPARTMENT OF COMMERCE
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Mary L. Good, Under Secretary for Technology

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Arati Prabhakar, Director

Precision Engineering/Precision Optics in Japan: Status, technology & culture

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Abstract:

Precision engineering and precision optics are commercially and strategically important enabling technologies. The character of precision engineering research and development in Japan is different from that in the US and Europe; these differences are the focus of this report.

Contents:

In an effort to strengthen U.S. competitiveness, see that U.S. industry becomes more aware of developments in Japan, and fulfill the mandate of the Japanese Technical Literature Act, the Department of Commerce's Office of Technology Policy Japan Technology Program has commissioned this report. The Japanese Technical Literature Act requires the Secretary of Commerce to prepare annual reports regarding important Japanes scientific discoveries and technical innovations

Precision Engineering/Precision Optics in Japan: Status, technology & culture

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Introduction:

Through the 1960's and 1970's United States technological dominance in what is now recognized as the discipline of precision engineering was generally taken for granted - at least in the United States. By the latter part of the 1980s it became clear that, at a minimum, leadership was dramatically diminished, if not lost. The character and the content of precision engineering activities in the United States, Europe and Japan differ; that difference is the focus of this report.

The author made two visits to Japan in 1993[*], attending two conferences and visiting a number of companies and institutions. Naturally, such brief exposure cannot produce any definitive survey; combined, however, with other visits to Europe and the technological literature, the visits allow some broad inferences to be drawn. Thus, this report will not repeat all the detailed observations contained in the trip reports[1], but will attempt to summarize them and put them into a broader context.

Precision engineering: what is it and why is it important?

To paraphrase the well known comment from the United States Supreme Court, precision engineering is like pornography; I cannot quite define it but I know it when I see it. Professor R.V. Jones, author of "The Wizard War" and longtime doyen of the precision instrumentation world, was not so limited; he defined precision engineering[2] as activities where the ratio of absolute size to smallest operationally significant variation is 10,000 or higher, going on to note that precision engineering "..embraces a wide range of activities ... the common feature being that it always demands abnormal care and trouble...." that breeds mutual respect and recognition members of "...an international freemasonry among those who strive for the best possible product". There have been many attempts at a definition[3] which can be summarized broadly as "manufacturing engineering and metrology at the limits of accuracy". Thus, precision engineering encompasses modern optical manufacturing, steppers, measuring machines, ultra-precision machining, laser based metrology, and so on.

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[*] Accompanied by K. L. Blaedel and D. C. Thompson in May 1993 and by J. S Taylor in October 1993, all of Lawrence Livermore National Laboratory

From this definition, and the oft felt need to define the technology, it should be apparent that precision engineering is not, of itself, a major economic market. Rather, it has -and historically always has had- significance both as a strategically important and as an enabling technology; precision engineers build nuclear weapons and night vision systems and they build the machines that make VLSI and compact disks possible.

Historical roots: common themes, technological contrasts, & cultural differences:

Modern precision engineering has roots in a number of disparate technologies (Figure 1) and is driven by:
* Strategic motives (defense);
* Commerce; and
* Science

In different countries the historical emergence of precision engineering took place at different times and under different circumstances. These differences are reflected today. Consider first the English. The first driver of precision engineering here was commerce - explicitly navigation. England was also first with the Industrial Revolution, forcing development of the essential infrastructure - machine building. In the United States, the early drivers mirrored the English experience, but took a substantially different turn in the late 1940s. Defense needs drove development, for example, of diamond turning technology. Substantial expertise developed in manufacture of low volume (high cost) high precision components and systems. Reconnaissance applications drove a substantial proportion of the precision optics development. Much of the work was secret.

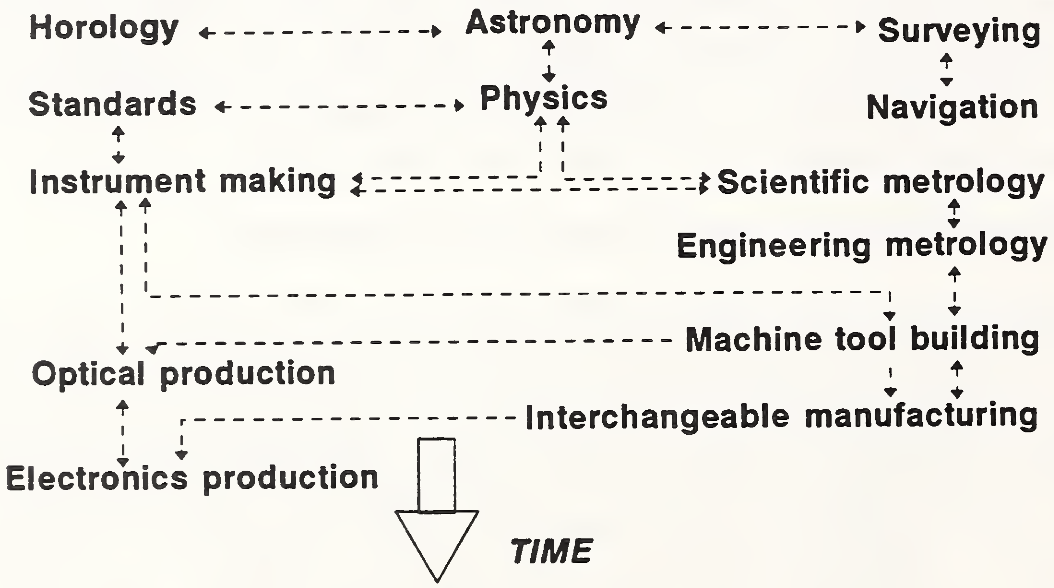

Figure 1. Historical roots in precision engineering. The dashed arrows indicate major interactions between application areas while time advances down the figure.

In Japan, circumstances could hardly have been more different. While the Industrial Revolution was in full swing in Europe and the United States, Japan was solidly entrenched in a period of isolation. With the Meiji restoration came industrialization -

based on Dutch machine tools bought from the Dutch traders who had controlled trade throughout the period of isolation and were still dominant. The end of World War II left a very different situation in Japan and, according to Tsuwa[4], spawned a very different route to the development of current precision engineering in Japan. Briefly, the war left Japan with essentially no industrial infrastructure; according to Tsuwa, the consensus was that Japan should first rebuild its industrial base, producing high volume, low cost, lower quality goods to obtain a reasonable share of world markets. Once that was achieved, quality could be improved. Obviously, the situation was more complex than Tsuwa's attractively simple portrayal; in the late 1940s, Osaka University had a Precision Engineering Department and the University of Tokyo had precision machine and precision machining courses[5] . Note, however, that even today much of what Japanese engineers call "precision engineering" would be considered "manufacturing engineering" in the United States or "production engineering in the United Kingdom. Whatever the details, however, it is clear that modern Japanese precision engineering has matured in the context of volume rather than small lot production.

This difference in roots may also have spawned another cultural difference between United States and Japanese precision engineering. The Japan Society for Precision Engineering (JSPE) was founded in 1944, the American Society for Precision Engineering (ASPE) in 1986. The Japan Society has broader coverage - taking an interest in higher volume, looser tolerance aspects of technology than would be accepted for consideration by ASPE. One consequence of this difference is that JSPE members employed in the manufacture of lower accuracy components are, at conferences and symposia, exposed to and interact with researchers pushing the limits of precision - to their mutual benefit. Thus, Japanese precision engineers probably have broader exposure to advancing technology than their American colleagues. This notion was reinforced by a comment made by H. Takeyama, president of the Kanagawa Institute of Technology, that "precision engineering is the foundation of all modern Japanese manufacturing".

Clubs and consortia:

Another mechanism for transfer of ideas, that as yet has few parallels in the United States, are "clubs" which, apparently, are common in Japan but which were quite a revelation to this author. Three examples of these clubs are:

* A diamond turning researchers club, described by Professor Moriwaki;
* The industrial precision machining group originally organized by Professor A. Kobayashi and which meets at the offices of the Japan Technology Transfer Association; and
* Professor H. Hashimoto's regional group based at the Kanagawa Institute of Technology.

It seems that these groups meet frequently - typically every 4-8 weeks. According to Professor Moriwaki, he does not always come away from the diamond turning research group having learned something new, yet he always knows the latest Japanese results. The system seemingly ensures that proper credit is accrued by developers of new ideas, while making those ideas immediately available for exploitation within Japan.

A similar ethos seems to pervade the more industrially oriented groups which have some invited speakers and some discussion meetings. From the response to talks by Evans, Blaedel and Thompson (May 1993 visit[1]), it was clear that the participants have as lively an interest in technology policy as in technical minutiae. Specifically, the response to Thompson's presentation about joint projects between Lawrence Livermore National Laboratory and manufacturing industry elicited numerous questions - and left the clear impression that this new use of United States Department of Energy resources was not in Japan's best interests! It was interesting to note that obvious competitors participate in these groups; discussions with club attendees led to the conclusion that the participating organizations are able to differentiate between generic technology (e.g. manufacturing methods, metrology) - which is shared - and product specific information, which is not.

The 7th International Precision Engineering Seminar (IPES 7) featured a "Pre-conference day" devoted to "International Developments in Precision Engineering". Two of the presentations, by Dr. A. Franks who discussed the United Kingdom National Initiative on Nanotechnology and by Professor M. Bonis on the French national program on precision engineering and their "Club Nanotechnologie", focused on organization rather than technological detail. It was noteworthy that both countries have established systems similar to the Japanese discussion "clubs" to provide low cost forums for rapid exchange of information.

Within the United States precision engineering/precision optics communities it is hard to identify any similar "clubs", nor mechanisms that provide equivalently rapid information exchange. There are consortia - for example the National Center for Manufacturing Sciences spindle project and the NIST organized ceramics machining consortium - but these typically revolve around collaborative projects with shared results. The professional societies, particularly ASPE and the Optical Society of America (OSA), organize topical meetings, although these tend to be slightly more formal and specific topics recur at intervals measured in years not weeks.

AMMTRA:

Consortia - such as SEMATECH and those referred to above - are a relatively recent feature of the United States technological landscape; in Japan, there is a much longer tradition of Government driven (and partially funded) collaborative projects. Among the better known of these are the 5th Generation Computer and the Yoshida Nano-mechanism projects.

Another such consortium is the MITI sponsored, Advanced Materials and Machine Tool Research Association with 20 member companies. Over the past 5 years it has undertaken coordinated projects ranging from excimer laser development, via improved displacement measurement and long range atomic force microscope development, to the construction of advanced grinders and polishing machines. Investment in AMMTRA by the Japanese government is $150 million (1986-93), which legally represents less than 50%, and based on conversations is more like 20%, of the total costs.

One major focus of the AMMTRA program seems to have been technology for ultra-violet (specifically 190-250 nm) wavelengths. In particular, the goal of the project seems to be

development of technology for development of free form aspheres diffraction limited for excimer lasers - but with surface finish appropriate for normal incidence soft X-ray projection lithography. This is a consistent, logical step from current lithographic practice (for IC fabrication) on the way to Soft X-ray Projection Lithography (SXPL -now often referred to as Extreme Ultra-violet Lithography (EUVL)).

Included in this project has been the development of a large grinder capable of producing substrates and, at Canon, a computer controlled polishing capability. They have built a machine with an integrated coordinate measuring station (using contact profilometry) with a 500 mm part capacity for free-form aspherics. This machine defines the current state-of-the-art in precision engineered machine design applied to polishing. It was only completed in early 1993, and a great deal of effort will be required in the next couple of years to really understand the new capability it offers. Preliminary results are impressive. At first sight, the target accuracy for free form aspheres - 80 nm P-V - seems too loose for one of the stated applications - soft X-rays. However, it is clear that the machine is appropriate for excimer and synchrotron optics and its designer (Negishi) also stated in a private conversation at the IPES 7 meeting that they assumed that higher accuracy (ie that appropriate for soft X-rays) would be obtained over the smaller apertures currently considered for soft X-ray projection lithography optics.

Another fascinating insight was the coordinated decision (or instruction?) within the AMMTRA project to do all manufacturing and metrology at 23 °C. When asked why they working at 23 °C when the international standard reference temperature is 20 °C, Negishi (Canon) stated "...but that is going to change". In fact, the international working group on the reference temperature for metrology has not accepted the proposal for change; indeed the meeting in January 1994 specifically rejected such a change.

Structure of R&D:

It is, perhaps, a tenet of faith in the occidental precision engineering community that “the precision engineering of today is the general engineering of tomorrow”. Thus we boost our own self-importance with the belief that our current frontier - often vilified as being out of touch with manufacturing reality - in fact represents the industrial future. As a self-confessed precision engineer, it is hard not to be impressed by both the volume and quality of research and development in precision engineering in Japan. Notably, the companies visited not only have substantial investments in precision engineering, but their overall R&D commitment matches the highest levels in the United States (Table 1). I am aware of no United States company with that has a precision machining research effort of the scale observed at Hitachi, Toshiba and Canon.

Table 1:

Company	R&D, $	R&D, % sales
Hitachi	*3.5 billion*	*10.3*
Toshiba	*2.4 billion*	*8*
Canon	*0.9 billion*	*6*
IBM	*5.6 billion*	*9*
Hewlett-Packard	*1.8 billion*	*9*

Hitachi, for example, has over 13,000 employees (approximately 16% of total work force) in research and development, spending 10.3% of gross sales ($3.5 billion). There are 9 separate research laboratories, at least two of which work on aspects of precision engineering.

Hitachi Central Research Lab has a total of 300 professionals - the elite of Hitachi. Of these, about 25 are foreign researchers on short term assignments - for example faculty on sabbatical or researchers from national laboratories. Precision machining has 22 staff (For comparison, the level of effort in the Precision Machining Research Facility at NIST is approximately 6 man-years/year). The focus for the Hitachi group is fundamental research funded by the corporation. They develop "elementary technologies" that will find use throughout the corporation. In precision engineering one example is kinematic slideways, the design of which would find use throughout the company. They also develop novel machines both for current product applications and longer term programs. An example of the latter is a polishing machine being developed to produced non-rotationally symmetric, normal incidence X-ray optics. The basic idea is to subdivide the lap into a number of sub-apertures, each mounted on a piezo with a load cell for feed-back. The pressure, and hence material removal rate, is varied as a function of rotational and radial position.

The Production Engineering Research Laboratory (PERL) does "all production engineering research for Hitachi"; 610 people work on projects of which 6% are "fundamental". Overall, 75% are "factory initiated" (and paid for, with a time frame of less than 5 years and typically nearer 2 years) and 25% are "independent research" - paid for by the corporation, with a time horizon greater than 5 years.

The Toshiba Manufacturing Engineering Research Center (MERC) is one of 17 research laboratories within Toshiba - 10 of which are located at plants and 7 paid for from corporate funds. Toshiba reinvests approximately 8% of gross sales in R&D ($2.4 x 10^9). In addition to being “the measurement center for Toshiba”, MERC has 400 staff addressing the following major areas:

* Fine technology - precision machining, equipment, motors etc
* Intelligent technologies - image processing, robotics
* Clean technology - thin films, LCDs
* Optical technology - solid state and excimer lasers
* Mechatronics - PCB assembly, assembly and production machines, micromotors

Such major support of R&D appears to be typical of many corporations with interests in precision engineering, precision optics and/or advanced lithography - including NTT, Canon, & Matsushita. It is hard to identify comparable corporate efforts - or comparably equipped corporate laboratories - within the United States. In contrast, however, compare efforts in precision engineering, precision machining and optical fabrication in the national laboratories in the United States with those in Japan; I am aware of no Japanese national laboratory that has an effort comparable to that at Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Los Alamos National Laboratory, or NIST. The closest example of a program in these areas is at The National Laboratory for High Energy Physics at Tsukuba, which has two diamond turning lathes, a 3 axis diamond mill, and two “home-built” shapers designed to make synchrotron optics. There is also some

work at the Mechanical Engineering Laboratory (MEL) in Tsukuba on precision machining, including dynamic analysis of diamond turning machines and grinding of ceramics. The level of effort is reasonable, but the trend downwards; MEL funding has been flat for the last five years, so spending capacity is dramatically reduced. Apparently there are very few technicians, leaving highly paid researchers doing work for which they are overqualified. According to Okazaki[6], this funding situation is the result of increasing fractions of government research funding going to the high profile national projects (such as the Yoshida Nano-mechanisms project, AMMTRA, etc).

The third arena for precision engineering R&D is within the University system. In the United States, reasonably sized research groups exist at North Carolina State University, and University of North Carolina at Charlotte, with emerging groups at MIT, Louisiana Tech, and UC Berkeley, and specific sub-sets of the topic are addressed at University of Wisconsin-Madison, Stanford, University of Arizona, Boston University, and University of Rochester. By contrast, the roster of Japanese universities with precision engineering programs is huge. It is not obvious that they are adequately equipped (by the standards, for example, of NC State, UNCC, or the United States national laboratories), but they do educate large number of students in the basics of precision engineering. Their published papers also reflect the large volume of work, the high percentage of that work that is carried out in collaboration with industry, and enough innovative thinking to give a lie to many Western stereotypes. For example, IPES 7 contained a large number of Japanese academic authored papers on aspects of precision machine design, on the fundamentals of advanced grinding processes, and one on perhaps the most unusual process revealed in some time: biological machining. Patterns can be laid down in photoresist on steel surfaces and then the appropriate bacteria provoked to, literally, eat away the metal. The bacteria are naturally occurring, suggesting a " green machining process" yet the controls would hearten any manufacturing engineer; metal removal rates seemed to be monotonic functions of input parameters - including applied voltage, stirring rate, etc.

Precision machining research and development:

The modern roots of what is now known as single point diamond turning are found in Philips in Europe and the nuclear weapons complex in the United States. The latter - especially Oak Ridge and Lawrence Livermore National Laboratory - drove the technology most visibly during the 1960s, 1970s and early 1980s, stimulating United States companies (notably Moore Special Tool Co and Pneumo Precision) to introduce standard diamond turning machines. Much of this early drive came from defense applications and, so, it is not perhaps surprising to find Japanese interest in the technology is more recent, tied presumably to growth in peaceful applications of precision machining. Given the availability, then, of commercially available diamond turning machines, the preponderance of "home-made" machines is somewhat surprising.

The Toshiba Manufacturing Engineering Research Center, for example, has a series of three in-house designed and built diamond turning machines. The claimed performance of the third machine matches the specifications of current state-of-the-art commercially available machines, although it exceeds that available at the time they must have made the decision to start building. The earlier machines did not match what was

contemporaneously available. The decision to build those machines is, however, comprehensible. Toshiba, like all big Japanese companies, know that virtually all graduate engineers joining them from college will remain with the company for the bulk of their careers. Thus, by building a cadre of engineers who have built the precision machines they then use to make components, they ensure in-house expertise. In effect, they invested in precision engineering by building what they could have purchased less expensively outside. The danger they face, of course, is insularity; expertise derived solely from in-house development tends to produce "design cultures" where designs are scaled up or down from previous models rather than thought out from first principles. Neither the machines at Toshiba nor the Canon polisher showed any sign of this "disease", however; perhaps the clubs and the copious Japanese literature in precision engineering provide the counterbalance that eliminates the possible detriments of their long term thinking.

At Hitachi Central Research Laboratories there were examples - combined in a single set of hardware - of home-built machines, of truly innovative thinking in machine design, and of a substantial national effort (with no evidence of coordination) to develop new technologies for synchrotron optic fabrication, a market sector which the United States currently dominates. The Hitachi approach uses a fly-cutter with the diamond tool mounted in a piezo-electric fast tool servo. Piezos were also central to an elegant design for a polisher for non-rotationally symmetric optics, such as the normal incidence soft X-ray optics needed for future lithographic applications.

Two other themes pervaded the precision machining activities observed in Japan; parallel efforts at different companies and vertical integration. One particular example was thin film heads for magnetic recording systems (eg Winchester hard disks for computers). Read-Rite Corporation in Milpitas, CA currently has about 50% of the world "commercial" market, buying ceramic wafers from domestic and Japanese sources, and relying on machines and tooling, as well as manufacturing technology from other domestic sources. Both Hitachi and Toshiba were developing not only manufacturing processes, but in-house materials and (eventually) the machine tools for production. Although visitors do not see the development of production machines, both Hitachi and Toshiba own subsidiaries that rank among the world's 20 largest machine tool companies. Thus each of these giants has or is developing under their own roof, control of the base material, development of the manufacturing process and construction of the production equipment. The R&D Division at Tokyo Magnetic Printing Co, a wholly owned subsidiary of TDK (a major manufacturer of thin film heads) is developing polishing media - particularly polyester films with diamond abrasives - which are being used to finish heads. Such vertical integration presumably offers guaranteed supplies and guaranteed quality.

Another area where there appeared to be substantial efforts - and which is currently dominated by relatively small United States companies - was synchrotron optics. The future size of this market will depend, to some extent, on the future of X-ray lithography; one estimate, however, is that it will be a multi-million dollar market. Traditionally, such optics have been torics (sections from the surface of a donut), having different radii in two perpendicular directions. Trends in synchrotron optics design are towards more complex, asymmetric aspheric surfaces. The new Canon polisher, for example, is clearly well suited to finishing such optics and several papers at IPES 7 described machine geometries

appropriate for making the basic optical figure. The Tsukuba High Energy Physics Laboratory has built two ‘shapers’ to produce such aspheric grazing incidence optics and worked with Professor Mori to implement elastic emission machining to post-polish the optics.

Considerable Japanese efforts are also obvious in the area of precision grinding of brittle materials - glass, silicon and ceramics. The Institute of Physical and Chemical Research (RIKEN), Tokyo is now the home base for Dr. H. Ohmori, pioneer with Professor Nakagawa (of Tokyo University) of the ELID (Electrolytic In-process Dressing) procedure for grinding with metal bonded grinding wheels. The physical facilities at RIKEN are a stark contrast to the impressive scale of the activity. Surface grinders, honing machines, flat laps, and silicon wafer polishing processes have all been fitted with ELID. In addition, Dr. Ohmori now has a Pneumo ASG 2500 producing aspheric optics; the surface quality on a BK7 asphere looked excellent to the naked eye, although no data on figure accuracy was offered. Ohmori has created the "ELID Team", a multi-company consortium including 4 non-Japanese groups. In the United States, similar work is starting, but is still way behind the Japanese.

At IPES 7 Nissin Machine Company showed an impressive centreless grinder - which would be very appropriate for rollers or fuel injectors, two probable future applications for precision ground ceramics. Nissin also built the grinder which Abe (Nippon Steel) used for ductile regime grinding of silicon wafers. The targets on total and local thickness variations seemed challenging - but appropriate for next generation lithographies. Notably, he also referred to optimization of ceramic vacuum chucks.

Hitachi Central Research Laboratory designed, built, and developed the manufacturing process for an aspheric lens generator built to grind finished (i.e. no polishing required) anamorphic glass lenses with approximately 20 μm departure from a base toric. One application of such lenses would be in optical scanners - indeed two machines are now producing optics at a Hitachi manufacturing plant.

Precision optics and lithography:

Integrated circuits is a massive market - estimated at $100 billion worldwide in 1994. Progress, over more than two decades, has been measured in terms of decreasing feature size on the circuit leading to bigger, better, faster memory and processing. The price of that progress has been new generations of optical lithography tools at amazing regularity. Ingenuity and good engineering have staved off the predicted demise of optical methods throughout the 1980s, but hard physical limits now stare the industry in the face. What constitutes the appropriate technological direction is not clear to the United States community, and that uncertainty also appears to afflict the Japanese; indeed the debates seem awfully familiar.

Toshiba, for example, is doing sub-micrometer lithography using an excimer laser based stepper; all optics are made by outside (presumably Japanese) contractors. The steppers in Toshiba plants at present use lasers acquired outside the corporation, although Toshiba is developing their own lasers which, presumably, will be used in the future. Toshiba stated that it currently has no plans to sell steppers.

At IPES 7 a Matsushita representative gave an interesting review of what appears to be a huge national program in proximity X-ray lithography. There are 10 synchrotrons in Japan where work in this area is taking place, dwarfing United States activities. The range of application of proximity lithography seems to be limited to feature sizes above 0.1 μm, and is getting squeezed by excimer laser based lithographies.

It seems that Hitachi, NTT, Canon and Nikon are all focusing their attention on Soft X-ray Projection Lithography (SXPL - or Extreme Ultra-Violet Lithography (EUVL)). Iizuka of Nikon rationalized this apparent divergence by pointing out that Matsushita has a 20 year investment in proximity and no capability to make optics; the optics companies - e.g. Nikon and Canon - can see routes to SXPL/EUVL based on their own core competencies. Iizuka was also persuaded, privately, to discuss Nikon's philosophy in future lithography. He stated, first, that they are a major supplier of steppers and intend to remain so and second that they have completely given up on X-ray proximity lithography. He commented that (a) the advances in optical techniques have closed the window of opportunity for proximity and (b) they developed, built, and sold a proximity stepper - and were unable to sell a second! Nikon will not get involved with phase shift masks; dealing with that array of problems, he argued, was up to the user. Nikon will produce probably two further generations of optical steppers using 248 and 193 nm radiation. Absorption at these wavelengths is a major problem, so Nikon has an aggressive policy of introducing aspherics to minimize the number of elements; ultimately, they will probably use some form of step-and-scan rather than step and repeat. Also, they make their own glass and are working to remove impurities to give the greatest possible uniformity. The parallel between this philosophy and recent results by SVGL Inc (Wilton, CT) and MIT Lincoln Laboratories is striking; a modified Micralign step and scan lithography tool operating at 193 nm is reported to have produced high aspect ratio, 0.1 μm wide lines over a 35 mm field. A major outstanding issue is the long term effect of densification of the quartz transmission optics due to operation at this wavelength.

Nikon fabricated the optics for, coated, and assembled the 32:1 Schwartzchild EUVL system used on a beam line at the SORTEC synchrotron which has so far only produced lines down to 0.5 μm. NTT and Hitachi also have working imaging systems; Hitachi, like Nikon, have a Schwartzchild system which has produced sub micrometer lines and spaces. The NTT system, using optics built by Tinsley Laboratories Inc (Richmond, CA), is a 5:1 two mirror off-axis aspheric system with a field (limited in part by the synchrotron radiation used) of 0.6 x 2 mm; budget imposed limitations on those optics limited resolution to 0.15 μm.

One general conclusion that many Japanese workers in the field emphasized echoed the conclusion of the recent workshop at NIST - that mirror figure metrology and fabrication are currently the most pressing problems. Next, perhaps, is affordable resists. Overall the Japanese work seems to have similar directions to work in the United States; there are efforts in multi-layer coating development (particularly to give controlled stress and graded coatings), in resist development, and in sources. The difference between United States (and European) and Japanese efforts seems primarily to be the scale of the effort.

Concluding remarks:

Precision engineering in Japan has a much higher profile than in Europe or the United States. Cultural and historical differences result in a different - commercial rather than military - emphasis. There is no fundamental reason why the United States should not lead the world in these strategically and commercially important endeavors; what is required is the recognition of the importance of the technologies, the base competence that already exists in the United States, and the will of industry and government alike to harness, and to invest in, that capability.

Acknowledgments:

Discussions with Kenneth L. Blaedel, Daniel C. Thompson, and John S. Taylor (all of Lawrence Livermore National Laboratory) both during and after the two trips to Japan were a key part of formulating the observations contained in this report. Thus, much of the credit is due to them, while any blame for any errors of commission or omission are entirely the author's. Professor H. Hashimoto made arrangements for the visits made in May 1993; without his generous help, much less would have been achieved in the time available. I would also like to thank W. Tyler Estler and Ken Yee(NIST), K. Blaedel (Lawrence Livermore National Laboratory), and Tamani Kusuda and Phyllis Genther Yoshida (Department of Commerce, Office of Technology Policy, Japan Technology Program) for reading drafts of this report, which was commissioned by the Japan Technology Program.

Appendix 1: Conferences attended, companies/institutions visited:

Conferences:

7th International Precision Engineering Seminar, Kobe, May 1993
Joint US-Japan Workshop "EUV Lithography for 0.1 micrometer and beyond", Hotel Mount Fuji, October 1993

Companies/institutions visited, key topics discussed, contacts:

Hitachi Central Research Laboratory:

Molecular manipulation - scanning tunneling microscope (STM) in a field emission scanning electron microscope with real time reflection high energy electron diffraction analysis. Use of STM to remove S atoms from MoS_2 surfaces.

Precision machining - fly-cutter with piezo-mounted tool for aspheric departure from conventional elliptical approximation to cylindrical optics. Aspheric grinder. Computer controlled (force controlled, full aperture) polishing.

Contact: Dr. S. Moriyama
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Tokyo 185
Tel: +81-423-23-1111

Fax: +81-423-37-7727

Hitachi Production Engineering Research Laboratory:

Electronics manufacturing: Multi-chip modules, automated PCB inspection, on-chip repair using 3D laser induced chemical vapor deposition and ion milling.

Precision machining: diamond turning, precision CBN machining of hard steels, post polishing, grinding. Lapping AlTiC thin film heads, tape polishing.

Contact: Dr. M. Masuda,
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Toshiba Manufacturing Engineering Research Center:

Lithography: excimer laser based steppers.

Precision machining: diamond turning, on-machine polishing with polymeric laps. Lapping AlTiC thin film heads. Precision wire EDM.

Electronics manufacturing: Multi-chip modules, automated PCB inspection.

Contact: M. Kamiya,
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Canon:

Computer controlled polisher and associated metrology

Contact: H. Narumi
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Kanagawa Institute of Technology:

Manufacturing technology

Ductile regime grinding

Contact: Dr. H. Hashimoto
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National Laboratory for High Energy Physics, Mechanical Engineering Center, Tsukuba :

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Nikon Tsukuba Research Center:

Advanced lasers and applications: Photon-echo microscopy, laser trapping/cooling,

Frontier technology for sensing; Scanning capacitance microscopy, scanning tunneling microscope based nano-lithography.

Basic technology for soft X-ray optics. X-ray microscopy, multi-layer coatings, projection optics for lithography, laser induced plasma sources.

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SORTEC Corporation:

X-ray proximity and projection lithography (hosted by K. Iizuka, Nikon Corp)

Institute of Physical and Chemical Research (RIKEN):

Electrolytic in-process dressing of grinding wheels, laps

Contact: Dr. H. Ohmori
RIKEN
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Fuji Die Corporation:

Electrolytic in-process dressing of grinding wheels, precision grinding of carbides.

Contact: T. Miyazawa
Fuji Die Co Ltd.
Diamond Tool Department
4-11-34 Tsunashimahigashi
Koohokuku
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Fax: +81-45-759-1555

Appendix 2: References:

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[2] Jones R. V. "Precision engineering: from silicon chips to supertankers" Precision Engineering, Vol 1 (1979), p3
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